Chapter 11

Recirculating Aquaculture Systems

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The oceans of the world were long considered to be an unlimited source of fishery products. Current estimates are that the maximum sustainable yield of many species through harvest of wild stock has been or will soon be reached, and many species are overfished. Yet due to the rapid increase of commercial scale aquaculture, production and per capita consumption of fishery products has been continuously increasing. Two examples of extremely successful aquaculture products that employ intensive recirculating systems at some stage of their growout are the salmon industry and tilapia. The Chilean salmon industry has grown from US$159 million industry in 1991 to exporting over US$2.3 billion in 2007 (498,000 tonnes). The production of tilapia has been exponential in the last several years to the point that the US market demand for tilapia has gone from essentially nothing to importing the equivalent whole fish of 554,000 tonnes in 2007.

Aquaculture is the most probable and feasible solution to providing the aquatic products for an ever-increasing market demand. It provides a consistent and reliable source of high-quality, fresh seafood that is nutritious, safe to eat, and reasonably priced. The basic thesis of this chapter is that Recirculating Aquaculture Systems (RAS) are the key technology that will allow the world aquaculture community to supply the world per capita needs for aquatic species over the coming decades and will do so in an environmentally friendly manner.

Aquaculture Production Systems, First Edition. Edited by James Tidwell.

In this chapter, we will review the basic unit operations that make up a RAS (e.g., oxygen supply, carbon dioxide removal, nitrogenous waste management including biological filters for ammonia removal, and solid waste removal). The main advantage of a RAS is that water quality can be managed to create the desired target environments for the fish being cultured, instead of the environment defining what fish can be grown. There are numerous ways to design a RAS, and most people who design such systems think that their design is the best. We do not attempt to define "best," but after reviewing this chapter, the reader should have a much better idea of how to go about designing such a system. There is no single system that will address all needs. Designs are often defined by economic constraints and availability of resources to farm owners. We have written a 948-page book on the design and management of RAS, and the reader is encouraged to read this book for further details on the various unit processes and management of such systems (see www.c-a-v.net).

11.1 Positive attributes

As a comparison, conventional aquaculture methods, such as outdoor pond systems and net pen systems, are *not* likely to be sustainable in the long term, due to significant environmental issues and their inability to guarantee the safety of their products to the consumer. Conversely, indoor fish production employing RAS is sustainable, infinitely expandable, environmentally compatible, and has the ability to guarantee both the safety and the quality of the fish produced throughout the year. Indoor RAS offer the advantage of raising fish in a controlled environment, permitting controlled product growth rates and predictable harvesting schedules. RAS conserve heat and water through water reuse after reconditioning by biological filtration using biofilters.

RAS allow effective economies of scale, which results in the highest production per unit area and per unit worker of any aquaculture system. RAS are environmentally sustainable: They use 90 to 99% less water than conventional aquaculture systems, less than 1% of the land area, and they provide for environmentally safe waste management treatment. RAS allow year-round production of consistent volumes of product, and complete climate control of the rearing environment. Because RAS can be set up to produce the same volume of fish every week, week in and week out, they have a competitive advantage over outdoor tanks, pond systems, or wild catch, which are seasonal and sporadic in harvest. Widespread usage of RAS has not yet been adapted for food fish production, mostly due to the high capital costs associated with most designs and the generally higher production costs for these systems, as water must be pumped. However, RAS are almost universally employed to produce salmon smolts, and designs continue to improve that are more cost competitive with conventional aquaculture systems. Recent economic studies on land-based salmon systems show that salmon can actually be produced more cheaply in RAS, but the capital costs are still too high to justify major changes in the way salmon are currently grown in net-pen systems.

RAS-designed aquaculture systems are infinitely scalable. There are no environmental limitations to the size of the intended fish farm to be built because waste streams are controllable in environmentally sustainable ways. Indoor aquaculture is probably the only potential method that could be used to ensure a 100% safe source of seafood, free from all chemicals and heavy metals. With increasing consumer concerns about food safety, aquaculture producers using RAS have an unprecedented opportunity to meet the demands for safe seafood. Attributes of fresher, safer, and locally raised products are clear advantages for RAS-produced seafood.

Over the past several decades, numerous recirculating system designs have been proposed and researched. Numerous commercial systems have opened with fanfare and have quietly gone out of business. Many of these early systems were designed using traditional wastewater treatment concepts and engineering, or by a simple trial and error approach. More recently, aquaculture engineering has come of age, and systems have been engineered specifically for aquaculture and the unique needs of an aquatic/biological system (Timmons & Ebeling 2010). In addition, numerous commercial sources of equipment and supplies are now available and are specifically designed and marketed for aquaculture. Species successfully being cultivated in intensive recirculating systems include tilapia, striped bass, cobia, pompano, barramundi, and marine shrimp.

What follows is an overview of the engineering aspects of intensive recirculating systems and system components as they have emerged over the past three decades. First, the concept of a "unit process" is introduced, where a specific treatment process is used to treat the water as it is recirculated through the system (i.e., solids removed, ammonia converted into nitrate, oxygen added, carbon dioxide removed, and, in some cases if necessary, disinfected). Then, examples of treatment technologies currently used are described and linked together in a complete recirculating system design. Finally, a design example uses the engineering concept of mass balance to show how to estimate water flow requirements for oxygen, ammonia removal, waste solid removal, and carbon dioxide removal. The majority of this chapter has been taken from Timmons and Ebeling (2010), and we recommend that the reader refer to this work for further explanation of the various concepts presented in the following sections.

11.2 Overview of system engineering

Engineers like to divide complicated systems into small parts, called unit processes, which correspond to a specific treatment process. Figure 11.1 shows how a recirculation system can be subdivided into several individual unit processes that may correspond to separate systems or be linked together in a process stream. There are numerous solutions to each "unit operation" and although some are more efficient or more cost effective than others, there is no right or wrong technology. Some work better in large-scale applications, some in small scale, but it usually is the case that all work to some extent. What final choice

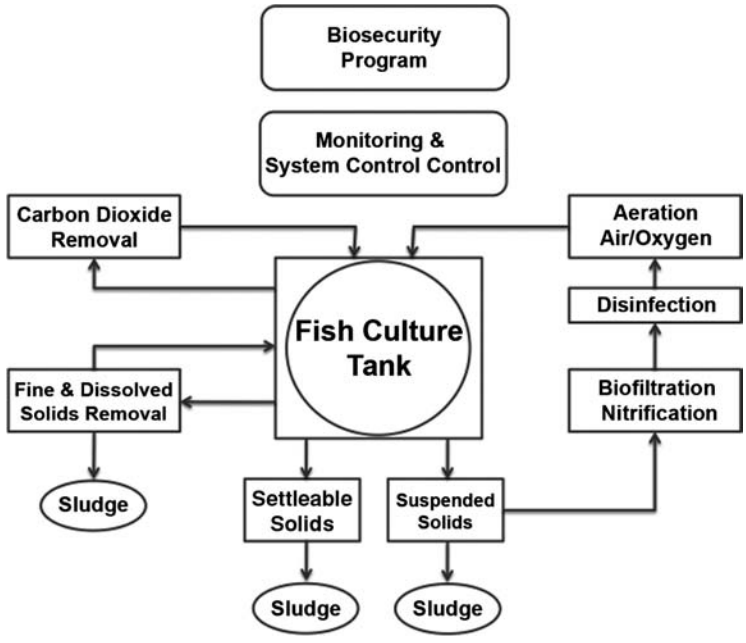

Figure 11.1 Unit processes used on a recirculating system.

is made should be based on sound engineering analysis of the options available for the species to be grown and what is appropriate technology or management for the region of the world in which the application will be implemented. And of course, as any good engineer knows, these choices must be made in the context of economic viability. A fish farmer must be profitable to stay in business, and an elegant design that produces beautiful fish but loses money is of no practical value to a fish farmer.

Returning to the process flow diagram in figure 11.1, the water moves from the central fish culture tank and flows through systems that remove the settleable and suspended waste solids, remove the fine and dissolved solids, convert the ammonia to nitrate, remove carbon dioxide and add oxygen, and finally, when required, disinfect the water before returning it to the culture tank. The monitoring and control system oversees all of these processes and controls the set points for water quality and sounds an alarm if they move outside of acceptable ranges. A biosecurity program and process must be absolutely superimposed on the whole process and farm to prevent losses due to disease introduction from the outside.

In a real world system, as many as possible of the individual unit processes are usually linked together as the water flows through each process (circulation). Usually 10 to 20% of the discharge flow from the culture tank is removed from the center drain to take advantage of the "tea cup" effect, which concentrates the solids in the central drain flow. Some form of settleable solids

removal device (swirl separator, radial flow clarifier, settling basin) pretreats this flow stream, which is then combined with the remaining 80 to 90% of the discharge from a side outlet. This combination of center drain and sidewall drain is usually referred to as a Cornell dual-drain system. The remaining suspended solids are then removed usually by either a rotating microscreen filter or floating bead filter.

The water then flows to some form of biofiltration, such as a trickling tower, bead filter, fluidized sand filter, or moving bed bioreactor, where the ammonia is converted to nitrate by autotrophic bacteria. At high loading densities, a carbon dioxide stripping column is then required to remove excess CO_2 and aerate the water to saturation. Finally, where high levels of stocking density are used (>60 kg/m^3) in commercial systems, an oxygenation device is employed to supersaturate the flow to provide sufficient oxygen. In some cases, a UV or ozone system is added to disinfect the returning water stream as part of a biosecurity program or where extremely high-quality water is required.

11.3 Culture tanks

Over the years, people have used a wide variety of materials to construct tanks, including just about anything that holds water. Simple molded polyethylene tanks are often used due to their low cost, smooth surface that makes for easy cleaning, and their low weight, which allows for quick set-up and relocation. They work well for the most part, but because they are very soft and malleable, they need to be well supported on the bottom.

Fiberglass is a popular choice for tanks because of its flexibility in both size and shape. Fiberglass tank panels are easy to cut, drill, and modify, and repairs are relatively easy. Large fiberglass tanks come in easily transported components that are field assembled to almost any diameter.

For maximum strength and resistance to abuse, galvanized or epoxy-coated steel modules can be bolted together to form tanks that are extremely large (32 m) and deep (4 to 5 m). The bottoms are usually poured concrete where drains and heating coils are embedded, along with the tank sidewalls. Tanks can be partially buried to conserve heat and make fish observations easier.

Concrete is always an option in making tanks. It is extremely strong, but very permanent. Mixed-cell raceway designs are another option for tank design, combining the advantages of a raceway for grading and sorting and a round tank for solids removal.

To promote mixing and solids removal, it is important that a tank has good hydraulic characteristics. One of the most important rules for RAS is that solids need to be removed from the tank as quickly and efficiently as possible to reduce the solids' impact on water quality. Tanks can be characterized by diameter (D) to depth (d) ratio (D/d). This ratio should be maintained greater than 3, less than 10, and preferably less than 5 (as in a deeper tank given the same diameter). Using this range of D/d will minimize the problems of solids settling

before reaching a center drain (indicating that a tank is too shallow; that is, an excessive D/d ratio) or not settling fast enough to reach the drain by being continually resuspended (indicating a silo-type tank that is too deep; that is, too small of a D/d ratio).

11.4 Waste solids removal

Waste solids are produced in an aquaculture system as uneaten feed, feed fines, fish fecal matter, algae, and sloughed biofilm cell mass from biological filters. Waste solids influence the efficiency of all other unit processes in the recirculating system. They are a major source of carbonaceous oxygen demand and nutrient input into the water and can directly affect fish health within recirculating systems. Therefore, solids removal is considered one of the most critical processes in aquaculture systems. Optimally, solids need to be removed from the fish culture tank as soon as possible, with minimum turbulence and mechanical shearing.

Solids are generally classified into three categories: settleable, suspended, and fine or dissolved solids. In recirculation systems, the first two are the primary concern, while dissolved organic solids can become a problem in systems with very little water exchange. Waste solids can be removed by either settling within the culture unit or through the use of a solids removal unit following the rearing tank. Several unit process options are currently being used in aquaculture: settling basins, radial flow clarifiers, mechanical filters, granular media filters, and floatation or foam fractionation.

11.5 Cornell dual-drain system

The Cornell dual-drain system uses the culture tank itself as a swirl separator ("tea-cup" effect) and removes most of the settleable solids from a small percentage of discharge from the center drain. This design system is applicable to round tanks and is very effective in removing the majority of large, quickly settleable solids such as uneaten feed and fecal matter using only a small portion of the total water flow (10 to 25%). This waste stream can then be further concentrated using either settling basins or additional swirl separators. Remember, the objective is to create a small, concentrated flow that is easily treated, rather than a large, diluted flow of waste.

Solids that concentrate at the bottom center can be removed in a small flow stream by using a bottom-drawing center drain, while the majority of flow is withdrawn at an elevated drain. The dual-drain system uses a center drain that removes from 10 to 25% of the flow and a higher sidewall drain for the majority of the flow (fig. 11.2). The location of the two tank drains has typically been at the center of the tank, which then takes advantage of both the tea cup effect and the strength of the overall flow when it drains through the tank center. The

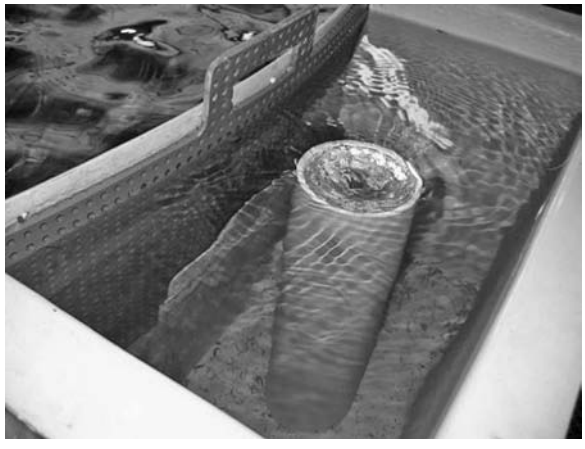

Figure 11.2 Sidewall discharge box with standpipe for water level control (75 to 90% of total discharge flow from rearing tank).

design criteria for the percentage of flow that should minimally be removed by the center drain are:

- 6 Lpm/m^2 (0.15 gpm/ft^2) of tank floor area
- Hydraulic retention time (HRT) center drain <200 minutes
- 15 to 25% of total tank flow rate.

After calculating these three values, the largest of the three values should be used.

A final criterion that should be applied to the drain design outlet is that the tank outlet should be approximately 10% of the tank diameter. This is because if the D/d ratio recommendation is followed, then solids should settle on the floor within about 5% (of tank diameter) of the tank center drain and be removed. For example, if a tank were 10 m in diameter, the center drain should have an effective diameter of 1 m (by using a flat plate slightly elevated above the tank floor) and the solids will settle within 0.5 m of the center point of the tank floor, thus these solids would be drawn into the center drain by high velocity created by the flow out the center drain. There are imaginative ways of achieving this besides making a large outlet drain: for example, flat plates on a center standpipe correctly spaced off the tank floor to create a desired capture velocity—at least 0.3 m/s—for the settling solids.

The alternative Cornell dual-drain approach has significant economic implications. When using this approach, solids removal costs are controlled more by the volume of flow that is treated rather than the solids concentration of the effluent that is treated. By concentrating the majority of the solid wastes in only 10 to 25% of the flow leaving a tank via the center low-flow drain treatment costs are proportionately reduced as well.

11.6 Settling basins and tanks

A settling basin is simply a tank that provides a quiet, nonturbulent area, where the flow rate is slowed and the solids are allowed to settle out of suspension by gravity. In an attempt to increase sedimentation, tube or plate settlers—consisting of a sequence of inclined tubes or plates that are stacked several centimeters apart—are often used. This increases the effective settling area per unit volume and reduces the depth to which a particle must settle to contact a surface. Advantages of settling basins are the simplicity of operation, low energy requirements, and their low construction costs. Disadvantages include the relatively large size of settling basins, their low removal efficiencies of small or low density particles, and leaching of nutrients from the settled solids back into the system while the solids are stored in the settling basin.

Another method to increase sedimentation rate is through the use of swirl separators or hydrocyclones. The effluent water from the culture tank is injected at the outer radius of a conical tank, so that the water spins around the tank's center axis. The spinning creates a centrifugal force that moves the particulates toward the wall, where they settle and can be removed continuously. These have most often been used in aquaculture recirculating systems to concentrate the solids from the dual-drain culture tank systems.

11.7 Mechanical filters

Two types of mechanical filters are commonly used in aquaculture to remove suspended solids: screen filters and expandable granular media filters. Suspended solids from an aquaculture viewpoint are within the fraction of total solids that will not settle out of the water column in a reasonable amount of time (30 to 60 minutes). This fraction of the solid waste needs to be removed from the culture tank water because of its potentially high oxygen demand and mineralization (the increased rate of ammonia-nitrogen being added to the water column as the protein and urea in the feces is broken down by bacteria into ammonia).

Microscreens are currently being widely used to remove suspended solids in both research and commercial recirculating systems. Microscreen filters act as a form of sieve that retains suspended particles larger than the fine mesh filter screen openings.

Rotating microscreen filters are available in a variety of sizes and flow rate capacities (fig. 11.3). They have numerous advantages, the primary one being that they are easy to install and operate. Almost all microscreen filters work on the principle of the physical interception of particles on a screen and their removal by means of a water spray. The screens are interchangeable and mesh size is usually selected based on the characteristics of the water to be treated, the required discharge water quality, and the trade-offs of size, cost, and waste discharge volumes. Microscreens are especially attractive when used to remove

Figure 11.3 Rotating microscreen filter and spray bars for cleansing.

solids from large flow streams. Additionally, they are compact in size and cause minimal head loss. The disadvantages of these systems are the high maintenance requirements and their relative high capital and operating costs. The performance of the microscreen filter is largely dependent on the size of the filter screen openings, influencing the filter's hydraulic capacity, the fraction of particles removed, the sludge-water production rate and concentration, and the filter backwash frequency that is generally discharged from the system (water loss that must be replaced).

11.8 Granular media filters

Granular media filters operate by passing water laden with suspended solids through a bed of granular material, which traps the solids through sedimentation, straining, and interception. The bead filters are the most popular form, due to their low head loss and low water requirements for backflushing. Bead filters have replaced the use of sand filters for all practical purposes. Sand filters can do a superb job at removing solids, where typically a sand bed is flooded from the top and the water is allowed to percolate through the sand. Sand filters, such as those used in swimming pools, operate under the same principle but use water pressure to force the solids-laden water through the sand. When the pressure requirements to push the water through the sand become excessive, then the sand filter goes into a backwash mode and in the process discharges large quantities of water. With either sand filter approach, excessive water loss occurs and the management of either sand filter has always been a challenge.

Bead filters employ small 3- to 5-mm low-density, polyethylene beads as the filtering media in pressurized, upflow filters. This type of plastic media is

commonly used as feed stock for plastic injection molding process. Filtration is accomplished by trapping suspended solids particles within the bead matrix and then periodically agitating the beads to settle out the trapped solids and biofloc. These filters have been successfully used for both solids capture and biofiltration. Traditionally, the chief disadvantage of this type of filter has been the large volume of water required for back-flushing (although much less is required than in a sand-filter design), although the PolyGeyser class of bead filters have successfully addressed this problem. For more details on bead filters see www.beadfilters.com.

Many of the fine suspended solids and the dissolved organic compounds that build up over time in intensive recirculating systems are not removed by mechanical filtration or granular media filters. These solids can be removed by using a process usually referred to as foam fractionation, air stripping, or protein skimming. In this process, air bubbles rising through a closed-contact column physically adsorb the fine suspended solids and dissolved organic compounds onto the surfaces of the air bubbles. The bubbles create foam at the top of the liquid column and the organic wastes can then be disposed of along with the foam produced.

11.9 Disposal of the solids

The solids generated by these removal methods can have significant impact on the environment if not disposed of appropriately. In general, aquaculture solid wastes are treated as an agriculture waste and considered a nontoxic nutrient source. Several options are utilized for disposal, including agricultural application on land and composting. Land application of waste solids to an on-site agricultural field is usually the cheapest methods of solids disposal. Land application is governed by regulations that limit the amount of pathogens, heavy metals, and other contaminants, nutrient content, soil type and plant nutrient-uptake characteristics to prevent run-off or groundwater contamination.

One of the newest techniques for containing sludge is to use geotextile bags (fig. 11.4). These are porous textile bags that receive the waste stream and capture solids while allowing the water to drain off for recapture. In many cases, a polymer or flocculation agent is added to the influent to improve solids/liquid separation. Alum or ferric chloride can also be added as a coagulation aid, which also helps to sequester dissolved phosphorus. Composting of waste solids using thermophilic bacteria creates a valuable soil amendment and also can be used to dispose of fish mortalities in a safe manner. Anaerobic and aerobic waste lagoons can be used, but will require careful engineering design to be properly sized and managed.

11.10 Biofiltration

Nitrogen is an essential nutrient for all living organisms and is found in proteins, nucleic acids, adenosine phosphates, pyridine nucleotides, and pigments. In the

Figure 11.4 Geotextile bag on gravel bed designed to capture leached water for reuse.

aquaculture environment, there are four primary sources of nitrogenous wastes: (1) urea, uric acid and amino acid excreted by the fish; (2) organic debris from dead and dying organisms; (3) uneaten feed and feces; and (4) nitrogen gas from the atmosphere. In particular, various nitrogenous waste products are expelled by fish through gill diffusion, gill cation exchange, urine, and feces. The decomposition of these nitrogenous compounds is particularly important in intensive recirculating aquaculture systems because of the toxicity of ammonia, nitrite, and to some limited extent, nitrate. The process of bacterial driven ammonia removal in a biological filter is called nitrification, and consists of the successive oxidation of ammonia to nitrite and finally to nitrate. The reverse process is called denitrification and is an anaerobic process where nitrate is converted to nitrogen gas. Although not normally employed in commercial freshwater aquaculture facilities today, the denitrification process is becoming increasingly important, especially in marine systems, as stocking densities increase and water exchange rates are reduced, resulting in excessive levels of nitrate in the culture system.

Ammonia, nitrite, and nitrate are all highly soluble in water. Ammonia exists in two forms, un-ionized NH_3 and ionized, NH_4^+, with the relative concentration primarily a function of pH and temperature. An increase in pH or temperature increases the proportion of the un-ionized form of ammonia nitrogen. For example, at 20°C and a pH of 7.0, the mole fraction of un-ionized ammonia is only 0.004, but at the same temperature the mole fraction increases to 0.80 at a pH of 10.0. Un-ionized ammonia is toxic to fish at low concentrations.

Nitrification is a two-step process, where ammonia is first oxidized to nitrite and then nitrite is oxidized to nitrate. The two steps in the reaction are normally carried out sequentially. Since the first step has a higher kinetic reaction rate than the second step, the overall kinetics are usually controlled by ammonia oxidation, and, as a result, there is usually no appreciable amount of nitrite accumulation. Equations 1, 2, and 3 show the basic chemical conversions occurring during oxidation by *Nitrosomonas* and *Nitrobacter* and the overall oxidation reaction (US EPA 1975).

Nitrosomonas:

$$NH_4^+ + 1.5\,O_2 \rightarrow NO_2^- + 2\,H^+ + H_2O \quad (1)$$

Nitrobacter:

$$NO_2^- + 0.5\,O_2 \rightarrow NO_3^- \quad (2)$$

Overall:

$$NH_4^+ + 2\,O_2 \rightarrow NO_3^- + 2\,H^+ + H_2O \quad (3)$$

Based on these relationships, 4.57 g of O_2 and approximately 7.14 g of alkalinity as $CaCO_3$ are needed for the complete oxidation of 1 g of ammonia-nitrogen. Alkalinity (all alkalinity is measured or defined in terms of calcium carbonate, $CaCO_3$) is generally added by using sodium bicarbonate/baking soda ($NaHCO_3$) or calcium carbonate, slaked lime (CaO), or hydrated lime, $Ca(OH)_2$. Sodium carbonate has the advantage of being rapidly dissolved and being very safe to handle (you can eat it if your stomach is upset!). Conversely, the various lime compounds are not easy to dissolve (mixing tanks are required) and they are dangerous to handle. The lime products though are often much less expensive per unit of alkalinity than baking soda.

The ammonia removal capacity of biological filters is largely dependent upon the total surface area available for biological growth of the nitrifying bacteria. For maximum efficiency, the media used must balance a high specific surface area (i.e., surface per unit volume) with appreciable voids ratio (pore space) for adequate hydraulic performance of the system. The media used in the biofilters must be inert, noncompressible, and not biologically degradable. Typical media used in aquaculture biofilters are sand or some form of plastic or ceramic material shaped as small beads, or large spheres, rings, or saddles. Biofilters must be carefully designed to avoid oxygen limitation or excessive loading of solids, biochemical oxygen demand, or ammonia. Several types of biofilters commonly used in commercial intensive recirculating aquaculture systems are: trickling biofilters, floating bead filters, fluidized-bed biofilters, downflow micro-bead biofilters, and moving bed bioreactors (MBBR).

11.10.1 Trickling towers

The trickling tower is a classical biofilter, combining both biofiltration, aeration, and degassing into one unit process. Water cascades over some media on which bacteria grow, oxygen diffuses into the water, and nitrogen and carbon dioxide diffuse out. They can be constructed to any diameter required. Effective distribution of the influent water over all the media both horizontally and vertically is a continual challenge.

11.10.2 Floating bead filters

Floating bead filters use beads that are slightly buoyant. The beads provide surface area for bacteria and also trap solids, thus doing two jobs for the price of one filter. Water is introduced below a bed of packed bead media and travels upward through the filtration chamber where mechanical and biological filtration takes place. Backwashing of the filter is accomplished either mechanically with a motor/propeller or with air bubbles (fig. 11.5). At some predetermined

Figure 11.5 Propeller washed bead filter for biofiltration and solids capture.

rate, a desired backwash or mixing cycle (after mixing and breaking up the static floating bed, the bed is allowed to settle for a minute or so, and then the settled sludge is discharged by opening a valve at the bottom of the filter) will be imposed to clean the beads and remove the resulting sludge. Newer designs for bead filters (PolyGeyser Drop Filters; see www.beadfilters.com) have the capacity to minimize water loss during the cleaning cycle. This is particularly advantageous in marine systems where the loss of saltwater is minimized and thus operating costs are decreased.

11.10.3 Fluidized sand beds

Usually used in large-scale cool or cold-water applications, fluidized sand beds provide large surface area for bacteria in a small footprint. These filters get their name because as the water flows up through the sand bed, the sand becomes suspended in the flow or fluidized. Numerous designs have been investigated and found to perform effectively, particularly for cool water applications that use fine sands. Fluidized sand beds can be relatively more expensive to operate than other filters due to the high pump rates and pressures required to fluidize the sand bed.

11.10.4 Downflow micro-bead biofilter

Downflow micro-bead biofilters have been used for several years due to their simplicity and low cost for media. The filters use small plastic beads (1 to 3 mm) that float in the biofilter as the water flows down through them. The high specific surface area, low head loss, and small footprint makes them a strong competitor to other biofilter designs. The Styrofoam micro-beads are also a fraction of the cost of other bead media.

11.10.5 Moving bed bioreactors

Moving bed bioreactors (MBBR) have been introduced over the last several years and appear to be one of the most competitive of all the biofilter types (fig. 11.6). The media remain in suspension as the water flows through the biofilter, which is actively aerated. The high turbulence and aeration provide good mixing and contract with the media.

11.11 Choice of biofilter

Each biofilter described has advantages and disadvantages that need to be taken in consideration during the early design phase. One of the chief advantages of

Figure 11.6 Media and discharge manifold in a MBBR.

both the trickling biofilter and the MBBR is that they both add oxygen to the water flow during normal operation. In addition, they can provide some carbon dioxide stripping. In contrast, the submerged biofilters, floating bead filters, micro-bead filters, and fluidized-bed biofilters are all net oxygen consumers and must rely solely on the oxygen in the influent flow to maintain aerobic conditions for the biofilm. If, for whatever reason, the influent flow is low in dissolved oxygen or the incoming flow to the biofilter is too low, interrupted anaerobic conditions will be generated within the biofilter.

The application of low specific surface area media is a distinct disadvantage for both the trickling biofilters and the MBBR. Since the capital cost is proportional to the total surface area of the filters, the result is physically large and requires more costly filters. In contrast, floating bead filters, and especially fluidized-bed filters and downflow micro-bead filters, use media with high specific surface area resulting in reduced cost and space requirements for the equivalent surface area.

11.12 Aeration and oxygenation

Dissolved oxygen is the first limiting factor in intensive aquaculture systems. Minimum dissolved oxygen concentrations of from 4 to 6 mg/L are required for optimal growth and survival of most aquaculture species. At densities up to 45 kg/m^3, aeration with atmospheric oxygen is adequate to maintain this level, and is commonly referred to as aeration. At higher stocking densities, pure oxygen is required and is usually referred to as oxygenation.

During aeration, air is brought into contact with water, either by bubbling air through the water or forcing small droplets of water through air. In each case, oxygen is transferred into the water and to some extent carbon dioxide and excess nitrogen are stripped out. In the oxygenation process, pure oxygen is used

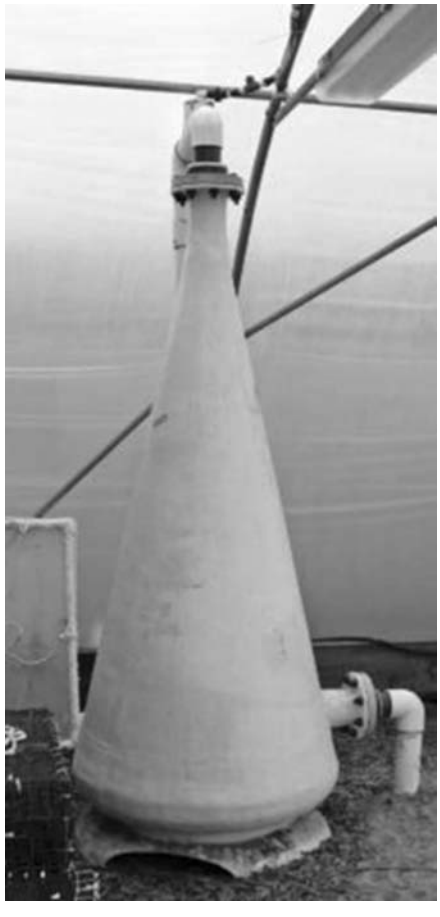

Figure 11.7 Speece cone for oxygen transfer.

to increase the transfer rate and yields supersaturated oxygen concentrations, theoretically five times that of aeration with atmospheric oxygen.

Oxygen can be produced on site using pressure swing adsorption (PSA) equipment or purchased in bulk liquid or gas form from commercial sources. Numerous types of oxygen transfer equipment are now available from commercial sources, including U-tubes, multistaged low head oxygenation units, packed columns, pressurized columns, oxygenation cones, oxygen aspirators, bubble diffusers, and enclosed mechanical-surface mixers. The two most often used in large-scale commercial systems are the downflow bubble contactor (Speece cones; fig. 11.7) or the multistage low head oxygenation (LHO) unit.

The downflow bubble contactor or Speece cone consists of a cone shaped column with water and oxygen injected at the top and removed at the bottom. As the water and the oxygen bubbles move down the cone, the downward velocity of the water decreases, due to the increasing cross-sectional area, until

it equals the upward velocity of the oxygen bubbles. This yields a long contact time between the oxygen bubbles and the water, resulting in oxygen diffusion efficiencies at or above 90%.

A multistage low head oxygenation unit (LHO) increases oxygen transfer efficiency by reusing the oxygen feed gas through a series of contact chambers. Water flow is distributed equally through a series of chambers via a perforated plate, flows through the chambers and into a pool of water, which seals the lower outlets. Oxygen gas enters at one side of the series of chambers and passes through each chamber due to the pressure variation across the unit. The repeated contact of oxygen and water in each chamber provides a high rate of gas transfer, both oxygen into the water and excess nitrogen out. LHOs provide moderate oxygen transfer efficiency and operate at very low-pressure heads. Gas to liquid ratios should be maintained at less than 1.5% to obtain reasonable transfer efficiencies (~70%).

11.13 Carbon dioxide removal

Carbon dioxide is a product of respiration of fish and other organisms in the production system, such as the bacteria in the biofilm. At low stocking densities, carbon dioxide is removed by the physical agitation and exposure of the water to air. But advances in recirculation system design and management have resulted in a steadily increasing stocking density of fish and a reduction in water exchange rates. As a result, carbon dioxide often becomes a limiting factor in some intensive production systems.

For every gram of oxygen consumed, 1.38 grams of carbon dioxide is produced. Carbon dioxide obstructs the respiration of fish by reducing the capacity of the blood to transport oxygen through a physiological phenomenon known as the Bohr effect. Carbon dioxide also directly affects the overall system performance by decreasing its pH, which can stress the fish and inhibit the nitrifying bacteria in the biofilters.

Carbon dioxide can be controlled by gas exchange in a downflow trickling tower or packed column aerator, similar to the downflow trickling tower used for biofiltration. As the water containing carbon dioxide flows over the media in the column, air is forced either up or down the column and carbon dioxide is removed by gas transfer across the thin water/air interface on the media surface. Carbon dioxide removal by gas exchange is often limited by the buildup of carbon dioxide in the gas phase, requiring gas to liquid flow ratios substantially higher than those needed for traditional oxygen or nitrogen gas transfers. Gas liquid (G/L) ratios should be maintained above 5 for effective removal conditions. Carbon dioxide concentration in culture waters will also be impacted by the alkalinity concentration of the water (i.e., for a specific pH value, carbon dioxide concentration is proportional to alkalinity concentration). In fact, there is a stoichiometric relationship between pH, carbon dioxide concentration, and alkalinity concentration; any two of these three variables defines the

third variable. See Timmons and Ebeling (2010) for a complete review of these relationships.

11.14 Monitoring and control

As the stocking density of fish continues to increase, the need for continuous monitoring and control of critical operations such as water flow, tank water level, and oxygen concentration also becomes essential to prevent catastrophic fish losses. It takes only one mistake to *kill everything in your facility!* For example, if a power failure occurred in a moderately stocked (60 kg/m^3) warmwater system, oxygen levels could drop to stressful levels in approximately 60 minutes—and if highly stocked (120 kg/m^3), in only 10 minutes.

Today, continuous monitoring systems are commercially available and relatively reliable. All the alarms should report to a phone dialer to notify staff both during and after working hours (the authors recommend twenty-four-hour people coverage wherever possible). Monitoring and control systems can be as simple as a solenoid valve that automatically opens an oxygen supply line to aerate during a power failure. For most facilities, simple, fairly inexpensive monitoring/auto dialer systems are commercially available, which will monitor eight or more switch inputs and automatically switch on backup systems and dial out in emergency situations. At the other extreme are sophisticated computer control systems that monitor multiple parameters with redundant backup systems, Internet pages for off-site monitoring, and phone dialers to alert management of system status and alarms.

Regular monitoring of other parameters that change slowly with time requires a well equipped and maintained water-quality lab (e.g., that tests for ammonia, nitrite, nitrate, alkalinity, etc.). It doesn't have to be an elaborate expensive facility, but it needs to be in a dedicated location with all the support equipment for good laboratory practices.

11.15 Current system engineering design

As can be seen from the above descriptions, there are several alternative solutions to each of the unit processes utilized in intensive recirculation aquaculture systems. Sometimes designing recirculation systems seems more like ordering from a Chinese menu, where the designer selects one unit from column A and another from column B and another from column C and then integrates them into the "optimal" design. Important design questions that determine what unit processes to use include: species to be produced, stocking density, production capacity, and sensitivity of species to water quality parameters such as temperature, dissolved oxygen, ammonia-nitrogen, pH, and CO_2. For example, tilapia is a species with excellent market potential and tolerance to poor water quality. On the other hand, many marine species of commercial interest have very high water-quality requirements.

Numerous combination and permutations of the above unit processes have been implemented over the past decade, and although no one system design has become the standard, several combinations seem to work well together. For example, many large-scale commercial recirculation systems use some form of a rotating microscreen filter for solids removal combined with a Cornell dual-drain system. Although microscreen filters have a high capital cost, their ease of installation and operation make them economically attractive. Most biofiltration is now accomplished with either a moving bed bioreactor (MBBR) or some form of granular media filter, such as a downflow bead filter or a fluidized-sand filter. The main advantage of the MBBR is the aeration and degassing they provide, reducing aeration or oxygenation requirements. Fluidized-sand filters have the advantage of lower capital cost and smaller size, but higher operating cost. Aeration and degassing of carbon dioxide is usually accomplished with some form of cascade column with high air:water volumetric ratios. Finally, oxygenation of the recirculated water is usually performed with downflow bubble contactors or LHOs.

11.16 Recirculation system design

11.16.1 Mass balances, loading rates, and fish growth

All system designs should begin with a mathematical analysis of the system loadings. This is how the various system components and unit processes are integrated to create a system that maintains targeted water quality parameters for some specific type of aquatic animal. Water flow is the mechanism by which oxygen is transported into a fish culture vessel and the waste products being generated within are removed. The design of a recirculating aquaculture system (RAS) should ensure that the important parameters affecting water quality and fish productivity (e.g., oxygen, ammonia, carbon dioxide, and suspended solids) are properly balanced. This requires calculating the required flow rates via mass balance equations to maintain the design water quality variables at or below (or above, in the case of oxygen) their maximum tolerable or design target values. Then the system must be operated at the highest flow rate calculated for these four critical water quality parameters. Obviously, the maximum flow rate used to maintain the constraining water quality parameter will be higher than necessary for the others, which simply means these water quality parameters will be at "better" values than design targets. The same mass balance approach can be utilized on any variable affecting water quality.

The mass balance approach simply comes down to balancing the transport in of some parameter, the production of this particular parameter within the culture tank, and the transport out of the parameter. In word equation form:

Transport **in** of X + **production** of X = transport **out** of X

The production term can be the production of oxygen, ammonia, suspended solids, or CO_2. Note that the production term can be *negative,* meaning consumption of a certain component (e.g., oxygen). Note that X does not refer to a concentrations of x, for example, in mg/L, but rather about a mass quantity of some "stuff," referred to as X in the word equation.

This is the control volume approach. Engineers like to depict mass transport across some "imaginary" box (unit processes) that designates the vessel or container that we are trying to analyze. For RAS it can be assumed that the culture tank represents a completely well-mixed tank and that the tank has reached a non-changing condition with respect to time or steady-state conditions. Each of the boxes shown in figure 11.1 represents some treatment device or process that changes the concentration of the noted parameter X. (Note: There could be several treatment devices, each treating a different water quality variable.)

Another way of representing the mass balance equation uses the product of the flow rate (volume/unit time) multiplied by the concentration (mass/volume) resulting in a mass per unit time, as, for example, kgs of oxygen/day, kg of solids per day, etc. Neglecting the effects of the flow-through component (which should be considered if the system discharge per day is one volume or more), the mass balance equation in its simplest form is:

$$Q\ C_{in} + P = Q\ C_{out}$$

C_{in}, C_{out}: Concentrations of parameter X into and out of the culture tank, mass/volume
Q: Water that is recirculated, mass/day
P: Production rate or consumption (negative), mass/day

11.16.2 Selecting tank values

The designer/manager must choose *design* or target operating conditions to calculate the mass balances. These are the C values in the mass balance equation. These design numbers are species dependent and are continually being refined for RAS applications. Calculating the minimum flows required to maintain targeted values for water quality (and then using the largest minimum value found for all the different water quality variables) will show how sensitive the calculated flow rates are to the value selected for the design value. A typical scenario is to select a value, do the calculations, realize that there is no way you could afford to supply such a high flow rate, and then start to make adjustments in the targeted values (for example, 4 mg/L oxygen is probably acceptable instead of the 6 mg/L you originally chose). In the end, one must choose realistic values at the beginning of the design process and then stay with these choices and the ramifications of the resulting flows required to maintain the mass balances. *Do not ever* compromise on the required flow rates.

11.16.3 Water treatment device

Each treatment box (unit process) is a system that "improves" the water quality of the water. The concentration of the particular water quality parameter leaving the treatment device can be calculated by knowing the "absolute" best the treatment device could achieve and the treatment efficiency of the particular device being used. The treatment efficiency should be provided by the device supplier or manufacturer.

Solving the general mass balance equation applied to the treatment box determines the concentration of each particular water quality parameter leaving the treatment device (C_2). The treatment device could be a biofilter, a CO_2 stripper, or a solids settling chamber. Each will have its own treatment efficiency for the particular water quality parameter it is designed to treat.

The water quality concentration C_{out} leaving the treatment box is found by using a mass balance analysis to be:

$$C_{out} = C_{in} + T/100\ (C_{best} - C_{in})$$

In this equation, T is the treatment efficiency (%) and C_{best} is the absolute best result obtainable by a treatment system (e.g., zero ammonia or saturated oxygen, zero suspended solids). Note that if the device is an oxygen addition unit, the C_{best} term can be increased above atmospheric concentration values for oxygen by increasing the partial pressure above atmospheric oxygen partial pressure in the device. For example, a pure oxygen device will have a C_{best} value of roughly five times the C_{best} value obtained if normal air were used at atmospheric pressure (e.g., trickling tower). C_{best} for most other parameters should be fairly obvious to the reader (e.g., ammonia and TSS are zero, but CO_2 will be around 0.5 mg/L since there is some CO_2 in the air).

11.17 Four major water-treatment variables

11.17.1 Oxygen

The major reason most fish die is from lack of oxygen due to a loss of water flow. This is because oxygen is consumed at a fairly high rate (fish metabolism) and oxygen is transported by water flow. Due to low inherent concentrations of oxygen, "high" flows are required to transport the required oxygen. Flows required to maintain a satisfactory oxygen level are generally the controlling flow rate parameter when solving the series of mass balance equations to determine the most restrictive parameter. Even a *partial* loss of flow will generally result in insufficient oxygen for the fish, resulting in death. Ask yourself if your monitoring system will sense a reduction in flow as opposed to a loss of flow.

It is important to remember that not only do the fish require oxygen, but also the biological filter, which is critically dependent upon adequate oxygen levels to

support bacteria metabolism. The dissolved oxygen (DO) concentration within the filter must be maintained at or above 2.0 mg/L to ensure that the rate of nitrification in the filter does not become limited because of oxygen depletion. Always measure the DO coming out of the biofilters and if the concentration starts to approach 2.0 mg/L, then take corrective action (e.g., increase flow rate through the biofilter by increasing the hydraulic loading rate on the filter or add oxygen prior to the flow entering the filter or within the filter itself).

The production term for oxygen (P_{Oxygen}) is:

$$\begin{aligned} P_{Oxygen} = & -0.25 \text{ kg per kg feed consumed by fish} \\ & -0.12 \text{ kg per kg feed consumed by nitrifying bacteria} \\ & -0.13 \text{ kg per kg feed consumed by heterotrophic bacteria} \\ & (\text{can be as high as } 0.5) \\ = & -0.50 \text{ kg (sum of above) per kg feed for system} \end{aligned}$$

These oxygen terms are all negative since they "consume" oxygen from the system as opposed to adding a mass quantity to the water column. The heterotrophic bacteria load can be as much as 0.5 kg of oxygen per kg of feed fed or higher if the system has poor solids removal. The oxygen consumption term is always much higher when solids management in a RAS is not good; a safe number for design purposes might be closer to 1 kg of oxygen per 1 kg of feed used (this would be twice as high as the above suggestion).

11.17.2 Ammonia

There is considerable confusion about design target values for ammonia concentration. Definitive values for the toxic levels of ammonia and the differentiation between the toxic NH_3 form and the supposed nontoxic NH_4^+ have not been precisely determined. The apparent toxicity of ammonia is extremely variable and depends on more than the mean or maximum concentration of ammonia.

The European Inland Fishery Advisory Commission (EIFAC) of FAO has set 0.025 mg/L as the maximum allowable concentration for un-ionized ammonia (NH_3 or ANH_3-N). A good rule of thumb is values of 1 mg/L for total ammonia nitrogen (TAN) for cool water and 2 or 3 mg/L for warmwater fish. You should always check your TAN target value selection by assuming some pH and temperature that you intend to maintain and see if your NH_3 concentrations will exceed the 0.025 mg/L value using readily available ammonia-ammonium pH temperature tables from several texts (Timmons & Ebeling 2010).

The rate of ammonia generation is considered to be a "soft" number. For simplicity, one could simply assume 10% of the protein in the feed becomes the ammonia-N generation rate. For a more precise estimate and one that is affected by protein content, the following equation for the production rate of ammonia

(P_{TAN}) can be used:

$$P_{TAN} = F \times PC \times 0.092$$

Here, F is the daily feeding level and PC is the protein content of the feed being fed. In this equation, the time period used is one day. In RAS, feed can be fed uniformly over a twenty-four-hour period, thus distributing the ammonia load uniformly over the entire day as well. If a uniform twenty-four-hour feeding is not used, then the above equation should be adjusted and the time period should be the time between feedings, or if a single feeding per day is used, then use four hours as the time period as an estimate of the time for the ammonia to be excreted from a feeding event. Note that in the above equation, the feed is assumed to be fed uniformly over a twenty-four-hour period. If the feeding period is concentrated to some fraction of the day, then the production equation for TAN must be accordingly adjusted upward. For example, if you feed over a twelve-hour period, then the P_{TAN} term will be twice as large for design purposes, requiring your biofilters to be twice as large (and cost twice as much!). This is why in RAS, you generally feed the fish over a twenty-four-hour period when possible.

11.17.3 Carbon dioxide

Carbon dioxide is an important, but largely overlooked water quality limiting parameter. This is probably because until recently, most systems were generally low density (less than 40 kg/m^3) and relied on aeration as the main means of supplying oxygen. This type of management also kept CO_2 values at low levels (e.g., less than 20 mg/L). However, loading rates have increased in recent years, and it has become necessary to inject pure oxygen into these systems, instead of using aeration. As result, the natural stripping of CO_2 that occurs when using aeration systems was no longer taking place. CO_2 production can be explicitly related to oxygen consumption as the ratio of molecular weights (44/32), $P_{CO2} = 1.375 \times P_{Oxygen}$.

11.17.4 Suspended solids

The effective control of solids generated in RAS is probably the most important task that must be accomplished to ensure long-term successful operation of a RAS. The quantity of suspended solids or total suspended solids (TSS) generated per unit of feed being fed is estimated as:

$$P_{solids} = TSS = 0.25 \times \text{kg feed fed (dry matter basis; range of 0.20 to 0.40)}$$

TSS is treated as a dilute waste. TSS design concentrations in RAS will be in the 10 to 100 mg/L range. Even after concentrating TSS with some type of treatment

process such as a rotating screen filter, the discharge water will still contain only around 0.5 to 1% solids on a dry matter basis. In comparison, cow manure is 20% solids. TSS captured in a settling basin has a fluffy consistency and will require substantial volumetric space depending upon frequency of cleaning. As a rule of thumb, assume that each kg of dry feed fed will produce approximately 25 liters of liquid waste (1% solids).

11.17.5 Nitrate nitrogen

Typically, nitrate nitrogen is not considered in the mass balance equations to determine maximum required flow rate. In saltwater systems, though, nitrate should be considered. Nitrate nitrogen (NO_3-N) is the end product of the nitrification process. In general, concentrations of nitrate are not extremely adverse to RAS water quality. Nitrogen is essentially conserved throughout the nitrification process. Thus, if 1 kg per day of TAN is being produced, then 1 kg of nitrate-N is being produced. The equilibrium concentration of nitrate will therefore be directly dependent upon the overall water exchange rate throughout the system. Nitrate-nitrogen is relatively nontoxic to freshwater fish and as such will not influence the controlling flow rates in the system. One can choose some value such as 200 mg/L, if you want a number to work with. More recent unpublished information seems to indicate that for various salmonids, the nitrate-N levels should not exceed 40 to 50 mg/L. Design information is very limited relative to this water quality parameter, especially for saltwater systems.

11.18 Summary of four production terms

These four terms are called the production terms, or the "P terms," in mass balance equations. Summarizing the four production terms as related to feed being fed is as follows:

$P_{Oxygen} = -0.50$ kg per kg feed consumed by fish

$P_{CO2} = 1.375$ grams produced for each gram O_2 consumed

$P_{TAN} = F \times PC \times 0.092$

$P_{solids} = 0.25 \times$ kg feed fed (dry matter basis; range of 0.20 to 0.40)

11.18.1 Predicting fish growth

The basic premise of RAS engineering is to produce a given volume of market size fish at some predetermined schedule. Based on the growth rate and stocking density, the size and number of production tanks can then be estimated. The production rate also defines the required fish feeding rate, which then in turn determines the waste generation loads (i.e., ammonia-nitrogen, carbon dioxide,

Table 11.1 Temperature growth units in °C (°F) for trout, tilapia, yellow perch, and hybrid striped bass.

	Trout	Tilapia	Yellow Perch	Hybrid Striped Bass
T_{base}	0 (32)	18.3 (65)	10 (50)	10 (50)
TU_{base}	6.1 (28)	3.3 (15)	5.5 (25)	5.5 (25)
T_{max}	22.2 (72)	29.5 (85)	23.9 (75)	23.9 (75)

solids) and also oxygen consumption rate. Based on these data, the most appropriate treatment systems can then be designed based on both water quality demands and economics.

A common way of defining fish growth is based on existing data sets of production trials under commercial stocking densities, feed rates, and water quality conditions. A second way is based upon a temperature unit approach and some defined number of temperature units to create a unit growth rate, such as centimeters per month:

$$Growth = \frac{T - T_{base}}{TU_{base}}$$

Where:

T = water rearing temperature

T_{base} = practical lower temperature where fish growth still is achieved

TU_{base} = monthly temperature units needed to achieve one unit of growth, e.g., 1 cm or 1 inch per month.

The above equation predicts growth, using units of cm/month or inches/month, and the T values are all in either degree Centigrade or Fahrenheit (see table 11.1 for values for various species; Timmons & Ebeling 2010). The growth equation is subject to the limitations that if T is greater than T_{max}, then calculate the growth at T_{max}. Note that excessive temperatures will compromise growth and/or feed conversion.

The weight of fish can be mathematically related to their length by using a term called the condition factor (K or CF); the bigger the condition factor, the more weight per unit length. The condition factor is expressed quantitatively using the equation below for either metric or English units. Each fish species will have an associated K or CF factor value to describe expected or normal body condition. The value of this factor is influenced by age of fish, sex, season, stage of maturation, fullness of gut, type of food consumed, amount of fat reserve and degree of muscular development. Typically, the condition factor will stay relatively constant from a very early fingerling stage (few grams) to near maturity size and, as such, is an excellent management tool for producers to determine over and underfeeding or poor water quality (causing high coefficient

of variation in the tank cohort).

$$WT(lbs) = \frac{CF\,(L_{inches})^3}{10^6} \text{ or } WT(g) = \frac{K\,(L_{cm})^3}{10^2}$$

11.19 Stocking density

The final and most important questions that must be addressed in system design is the mass of fish that can be maintained in a tank or, more appropriately, the mass of fish that can be maximally supported. We should probably call this term the harvest density (or the density that when reached will trigger an action by the fish manager to move the fish to their next stage or be taken to market). The number of fish and their individual weight will define the feeding rates from which all other individual engineering components are designed. The mass of fish that can be stocked (or harvested) per unit volume ($D_{density}$) will depend on both the fish species and the fish size. We use an approach that is based upon body length (L) to estimate the number of fish that can be carried per unit volume of tank:

$$D_{density} = \frac{L}{C_{density}}$$

Where:

$D_{density}$ Density in kg/m^3 (lb/ft^3)

L Length of fish in cm (inches)

$C_{density}$: 0.34 for L in cm (2.1 for L in inches) for a trout species (different species have their own $C_{density}$ value).

Maximum allowable or safe densities (D_{fish}) for fish stocking is primarily a function of fish size, species, and the characteristics of the rearing environment and management skill. New growers tend to overestimate their own safe loading densities and assume they can establish and sustain densities from the very beginning that in fact require expert management skills. *Do not fall into this trap*. You will kill fish. New growers should target about half the densities recommended for expert growers. For example, a tilapia system for a new grower should probably be operated at a maximum density of 50 kg/m^3 rather than 100 to 120 kg/m^3.

11.20 Engineering design example

11.20.1 Required minimal flow rates

Let's assume a target production capacity of 500 metric tonnes of tilapia per year with a target market size fish of 750 g (1.65 lb), whole, on ice. Tilapia

Table 11.2 Condition factors for various fish (Timmons & Ebeling 2010).

Species	CF (length in inches, weight in lb)	K (length in cm, weight in g)
Tilapia	750–900	2.08–2.50
Tilapia <1 gm	500	1.39
Rainbow, Brown Trout	400	1.11
Lake Trout	250	0.69
Charr	520	1.45
Hybrid Striped Bass	720	1.99
Perch	490	1.36
Muskellunge	150	0.42
Northern Pike	200	0.56
Largemouth Bass	450	1.25
Walleye	300	0.83

fingerlings are purchased at a mean size of 50 g. A three-stage production system is decided upon (i.e., fingerling, intermediate, and growout).

Step 1: Calculate growth period from stocking to harvest

The following calculation is employed to determine the total growth period required from 50 grams to 750 grams, at 28°C (83°F); assume a K = 2.10 (CF = 760; see table 11.2 for tilapia). Calculate length of fingerlings at 50 g and the final market sized fish at 750 grams:

$$L\,(cm\,at\,50\,g) = \left[\frac{100 \cdot 50}{2.10}\right]^{1/3} = 13.4\text{ cm}$$

$$L\,(cm\,at\,750\,g) = \left[\frac{100 \cdot 750}{2.10}\right]^{1/3} = 33.9\text{ cm}$$

Total change in length required from 50 to 750 grams:

$$\Delta L = (32.9 - 13.4) = 19.5\text{ cm}$$

Step 2: Determine time for growout

Calculate growth rate at the specified rearing temperature of 28°C (83°F):

$$Growth_{rate} = \frac{28 - 18.3}{3.28} = 2.96\frac{cm}{month}$$

Total time to achieve the required length:

$$Growth_{period} = \frac{19.5\ cm}{2.96\frac{cm}{month}} = 6.6\ months$$

Step 3: Determine production strategy

Note that this growth could occur in a single tank and the fish remain there for 6.6 months, or the growth could be managed to occur in three tanks that are managed sequentially. If a three-stage scheme is used with equal time at each state, then the fish would reside in each tank for one-third of the total growth time, or 2.2 months/size class, or 9.5 weeks in each tank; in practice, we'd probably round this up to ten weeks.

A very simple concept here that is sometimes missed is that whatever the production cycle is for a stage will determine how many tanks are needed for that stage. If ten weeks are required for the final production stage, and weekly harvests are required, then ten final growout tanks will be required. The other twenty weeks of the growout cycle can be distributed however you choose, but their cumulative growth time must add up to twenty weeks. More commonly, the time the fish stay in stage 3 might be increased (e.g., stage 1 for four weeks, stage 2 for eight weeks, and stage 3 for eighteen weeks) so there is less stress on moving fish from stage 2 to stage 3 (this scheme allows you to move smaller fish, which is always easier).

To keep things simple in this example, assume that the fish will be kept in each stage for an identical time. This will require designing a fingerling to growout production strategy that requires ten tanks (rounding the 9.5 weeks to 10 weeks) per stage of increasing size, plus systems for circulation, solids removal, biofiltration, and gas exchange. During each stage, the change in length of the fish would be the total increase (19.5 cm) divided by the number of stages (three) or 6.5 cm. Using the length/weight relationship, the initial and final weights can be calculated at each stage as shown in table 11.3.

Step 4: Calculate weekly harvest weight

Assume that fifty weekly harvests are conducted with a two-week end of year vacation break:

$$Harvest_{weekly} = \frac{500{,}000\ kg/year}{50\frac{weeks}{year}} = 10{,}000\ kg\ per\ week$$

Step 5: Determine the number of fish per tank at harvest

Note that no allowance was made for mortalities, but they are a part of life and are best estimated based on actual production experience.

$$Fish_{Tank} = \frac{10{,}000\ kg}{750\frac{g}{fish}} * \frac{1000\ g}{1\ kg} = 13{,}333\ fish\ per\ Tank$$

Step 6: Estimate final tank biomass at each stage

$$Biomass_{Tank} = 13{,}333\ fish\ per\ Tank^{*} Weight_{Final}$$

Step 7: Estimate final feed rate per tank

Using the steps previously shown (calculate the weight of the fish the day before harvest), calculate the amount of feed used on the last day for the end

Table 11.3 Initial and final weights and lengths of the three-stage production strategy.

	Initial Wt Size	Final Wt Size	Final Tank Biomass	Feed Rate (% bw/day)	Final Feed Rate
Stage 1:	50 g 13.4 cm	165 g 19.9 cm	2,200 kg	2.81%	62 kg
Stage 2:	165 g 19.9 cm	386 g 26.4 cm	5,146 kg	2.12%	109 kg
Stage 3:	386 g 26.4 cm	750 g 32.9 cm	10,000 kg	1.70%	170 kg

of each stage. Table 11.4 shows the key calculation parameters for the growout stage. The final feeding rates per tank at maximum biomass density for the other stages are summarized in tables 11.3 and 11.4.

Step 8: Determine the controlling flow rate for this design problem (i.e., dissolved oxygen, carbon dioxide stripping, or ammonia-nitrogen removal)

Calculate the required design flow rate for a 100% recirculating flow for the production tank feeding rate of 170 kg feed/day at 38% protein. Calculate the required flow rate for each water quality parameter and then identify the controlling parameter. Compute the required steady-state flow rate for maintaining the following water quality levels: 2 mg/L TAN, 5 mg/L O_2, and 40 mg/L CO_2. (In this example, we are neglecting TSS, which is rarely, if ever, the controlling flow rate.) Assume the following efficiencies for the treatment devices: 35% for TAN, 90% for O_2, and 70% for CO_2. Additionally, the tank water temperature was set to 28°C, and the C_{sat} in the O_2 treatment device is 18.1 mg/L (it uses some pure oxygen).

Start with the General Mass Balance, where C_1 is outflow and C_2 is inflow from the fish culture tank:

$$QC_2 + P = QC_1$$

$$\text{or} \quad Q(C_1 - C_2) = P$$

Table 11.4 The key calculation parameters used for the growout stage.

Growth, cm/month	2.96
Growth, cm/day	0.0970
Length at harvest, cm	32.9
Length, day -1	32.803
Final weight, g	750
Condition factor (K)	2.10
Weight, day -1	741.239
Change in weight, g/fish	8.7613896
Feed Conversion (FC)	1.46
Number of fish	13,300
Total daily feed, kg/day	170

11.20.2 Required design flow rate for dissolved oxygen

Looking initially at Dissolved Oxygen, as this is often the controlling parameter for flow, first calculate the influent dissolved oxygen concentration (C_2) using a Speece cone with 90% oxygen transfer efficiency (TE) and a production tank DO level (target value for minimum) of $C_1 = 5$ mg/L.

$$C_2 = C_1 + TE\ (C_{sat} - C_1)$$

Solve for C_2, and you obtain:

$$C_2 = 5.0 \text{ mg/L} + 0.90^*(18.1 \text{ mg/L} - 5.0 \text{ mg/L})$$
$$C_2 = 16.8 \text{ mg/L}$$

Oxygen production, that is, consumption or (-P), is the sum of fish and bacterial oxygen consumption:

$$P = \frac{0.25\ kg\ O_2\ by\ Fish}{kg\ feed} + \frac{0.12\ kg\ O_2\ by\ Bacteria}{kg\ feed} = \frac{0.37\ kg\ O_2}{kg\ feed}$$

$$P = \left(\frac{170\ kg\ feed}{day}\right)\left(\frac{0.37\ kg\ O_2}{kg\ feed}\right)\left(\frac{10^6\ mg}{kg}\right) = \frac{62{,}900{,}000\ mg\ O_2}{day}$$

Note that using 0.37 kg oxygen per kg of feed would be the lowest demand one would use for design purposes. This would represent the case where either a trickling tower or a MBBR is to be used. As previously discussed, using a value of 0.5 to 1.0 for oxygen demand (as opposed to 0.37 in this example) would be a more conservative approach to ensure sufficient flow for all oxygen demands in the system.

Returning to the General Mass Balance for a RAS:

$$Q_1\ C_2 + P = +Q_1\ C_1$$
$$Q(16.8 \text{ mg/L}) + (-62{,}900{,}000) \text{ mg/day} = Q(5.0 \text{ mg/L})$$
$$Q = \frac{\dfrac{62{,}900{,}000\ mg\ O_2}{day}}{(16.8 - 5.0)\dfrac{mg\ O_2}{liter}} = \frac{5{,}330{,}000\ liter}{day} \quad or\ 3{,}700\ Lpm$$

Summarizing this calculation, approximately 3,700 Lpm (975 gpm) of influent water at 16.8 mg/L DO is required to satisfy the oxygen demand of the 170 kg of feed per day.

Table 11.5 Summary required flow rates for the production tank.

Water Quality Parameter	Required Flow rate
TSS	3,940 Lpm (1,040 gpm)
TAN*	5,900 Lpm* (1,560 gpm)
Oxygen	3,700 Lpm (975 gpm)
Carbon Dioxide	1,280 Lpm (575 gpm)

Note: *Controlling flow rate.

The other flows for the other water quality parameters are then calculated in a similar manner. The resulting flow rates are shown in table 11.5. The maximum flow rate calculated for any parameter is the *only* flow that guarantees that all the water quality parameters will meet the requirements set. In this case, the controlling flow rate is 5,900 Lpm (1,560 gpm), which was calculated for TAN. At this stage, each of the selected unit processes can be reexamined to determine if more efficient units could be selected that reduce the required flow rate. For example, the biofilter efficiency might be increased by increasing the hydraulic retention time on the bioreactor vessel, thus increasing its efficiency (of course this has capital cost considerations as well). A balance needs to made between the capital cost of equipment and the long-term operational cost of operation and pumping of water.

11.20.3 Calculating tank sizes

The last step in our design process is to determine the tank sizes necessary for each of the three stages for our 500-tonne production farm. The tanks sizes can be determined based on the allowable fish biomass stocking densities. As previously determined (see table 11.3), the final fish biomass per tank was 2,195 kg for the fingerling stage 1; 5,134 kg for stage 2; and 10,000 kg for the growout tank stage 3. Note how the systems support larger biomasses of fish as the fish increase in size. This is because the fish require space (room) by length and not by body mass, and mass is proportional to length cubed.

Using the density equation, the corresponding stocking-harvest densities can be calculated. That is, for the stage 1 system at harvest, the density when moving from stage 1 to stage 2 is:

$$D_{Stage\ 1} = \frac{L}{C_{density}} = \frac{19.9\ cm}{0.24} = 82.9\frac{kg}{m^3}$$

Correspondingly, the stage 2 final tank density is 110 kg/m^3 and the growout tank stage 3 at harvest is 137 kg/m^3. The required volume of each tank for each of the three stages is equal to the total biomass for that stage's cohort of fish

Table 11.6 Final tank biomass density and tank dimensions for the three-stage production strategy.

	Fish Density kg/m^3 (lb/gal)	Tank Volume m^3 (gal)	Tank Depth m (ft)	Tank Dia. m (ft)
Fry production	82.9 kg/m^3 (0.69 lb/gal)	26.5 m^3 (7000 gal)	1 m (3.2 ft)	5.8 m (19 ft)
Fingerling	110 kg/m^3 (0.92 lb/gal)	46.6 m^3 (12,300 gal)	1.2 m (3.85 ft)	7.0 m (23 ft)
Growout	137 kg/m^3 (1.14 lb/gal)	72.8 m^3 (19,200 gal)	1.5 m (3.85 ft)	7.9 m (26 ft)

divided by the stocking density, or for example:

$$V_{Stage\ 1} = \frac{W_{fish}}{D_{fry}} = \frac{2195\ kg}{82.9 {}^{kg}/_{m^3}} = 26.5\ m^3$$

Assume that for management reasons, the tank depth is approximately 1 m in the fry tank (so the area of the tank is 26.5 m^2). And from simple geometry, the tank diameters can be determined for stage 1:

$$Dia_{Stage\ 1} = \sqrt{\frac{4\ area}{\pi}} = \sqrt{\frac{4\ 26.5\ m^2}{\pi}} = 5.8\ m$$

Increasing the depth to 1.2 m for the stage 2 tanks and 1.5 m for the growout stage 3 tanks yields diameters of 7 m (22.6 ft) and 7.9 m (26 ft), respectively. Table 11.6 summarizes the tank biomass design and sizing. Note that these calculations are based upon equal time in each stage of the three-stage production strategy. Also, remember that for each stage in our example, there are ten weeks, so this means that ten tanks of the determined dimensions for each of the three stages are required for the production farm, or a total of thirty tanks are required.

11.21 Conclusion

The design and engineering of intensive recirculating aquaculture systems has made significant progress over the past several decades. Systems components have been designed and engineered specially for aquaculture, and are field tested and available from several commercial sources. System integration is just beginning to be investigated to determine optimal configurations of an overall system design based on species, production levels, and water quality requirements. Even with all the successes and improvements, though, it is still challenging to implement and manage recirculation systems that are cost competitive with other less capital-intensive production strategies.

11.22 References

US Environmental Protection Agency (1975) *Process Design Manual for Nitrogen Control*. A design manual prepared for the Office of Technology Transfer of the US EPA.

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